Status of the NectarCAM camera project

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ABSTRACT

NectarCAM is a camera designed for the medium-sized telescopes of the Cherenkov Telescope Array (CTA) covering the central energy range 100 GeV to 30 TeV. It has a modular design based on the NECTAr chip, at the heart of which is a GHz sampling Switched Capacitor Array and 12-bit Analog to Digital converter. The camera will be equipped with 265 7-photomultiplier modules, covering a field of view of 7 to 8 degrees. Each module includes the photomultiplier bases, High Voltage supply, pre-amplifier, trigger, readout and Thernet transceiver. Events recorded last between a few nanoseconds and tens of nanoseconds. A flexible trigger scheme allows to read out very long events. NectarCAM can sustain a data rate of 10 kHz. The camera concept, the design and tests of the various subcomponents and results of thermal and electrical prototypes are presented. The design includes the mechanical structure, the cooling of electronics, read-out, clock distribution, slow control, data-acquisition, trigger, monitoring and services. A 133-pixel prototype with full scale mechanics, cooling, data acquisition and slow control will be built at the end of 2014.

Keywords: Gamma-ray astronomy, camera for Cherenkov telescopes, NectarCAM, CTA

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1. INTRODUCTION

NectarCAM is a new camera design for the medium-sized telescopes of the planned CTA, an array of imaging atmospheric Cerenkov telescopes (IACTs). IACTs detect gamma-rays in the very high energy range, with energies ranging between a few tens of GeV and a few hundred TeV. The sources of these photons are cosmic-ray acceleration sites such as pulsars and pulsar wind nebulae, blazars and possibly exotic contributions such as dark matter annihilation in galactic halos. While current generations of IACT arrays had just a few (≤ 5) telescopes, CTA will have tens of telescopes with different dish sizes to cover the whole energy range with sufficient sensitivity. More information on the CTA design is given by Acharya et al[1] or on the CTA web-site *. Single-mirror medium-sized telescopes (MSTs) with 12-meter diameter reflectors will cover the 0.1 TeV to 10 TeV energy range. They are improved versions of the VERITAS and H.E.S.S. telescopes. The main differences are a larger field of view (7^o compared to 5^o), more accurate timing measurements, a larger data transfer rate, and an improved reliability which will allow the camera to be operated tens of years with minimal maintenance.

The principle of NectarCAM operations is presented in Section 2. The prototyping strategy is briefly explained in Section 3. The trigger system and the readout are described in Sections 4 and 6. The design of mechanical structure is then described in Section 7. Finally, the photosensors, the acquisition system, the monitoring and the power supplies are presented in Sections 5, 9 and 8 respectively.

2. PRINCIPLE OF NECTARCAM

TeV photons create an electron-positron shower in the Earth's atmosphere. The relativistic electrons and positrons emit Cherenkov light. IACT image the core of the shower at the focal plane of a telescope. The photon image is roughly elliptical, with a typical $0.2° \times 1°$ extension which increases with energy. The location of the pseudoellipse in the camera is correlated with the distance to the shower impact on the ground. Energetic showers can be seen at larger distances and appear at the edge of the camera. IACT cameras have pixels which are either photo-multipliers or more recently SiPM. NectarCAM uses photomultipliers which have a field of view of 0.18° when mounted on the MST telescope. The Cherenkov light signal from photon showers arrives in less than 5 ns in individual pixels. However, the arrival of the photons from a distant shower has a gradient over the major axis of the pseudoellipse and can last more than 100 nanoseconds.

IACTs have two major sources of background: night sky background (NSB) and hadronic showers. NSB is light from stars and diffuse light such as zodiacal light seen by the camera. The first step in removing the NSB is to optimize the signal to noise ratio by imaging the sky only in a small time-window during the shower event. NectarCAM records events which are 10 to 60 ns long. The second step is to require a minimal amount of energy detected in a small region in the camera. This is the role of the trigger system, described in detail in Section 9. The second source of background comes from the particle showers initiated by charged cosmic rays, mostly hadrons, in the atmosphere. Cherenkov light comes from electromagnetic showers induced by pions and muons and is patchy both in space and time. Hadronic background can be separated from gamma-ray signal by applying topological cuts to the image. The hadron trigger rate is typically 3 kHz, many order of magnitudes larger than the photon signal from cosmic sources (typically 10^{-2} Hz).

NectarCAM has a modular architecture similar to the H.E.S.S.-2 camera,[2] which has the advantage of avoiding costly cables and allowing for easy maintenance. The basic unit is the Nectar module, which converts the light from a set of photomultiplier tubes (PMTs) into a digital signal when some triggering conditions are fulfilled. It is described in detail in Section 6. Figure 1 shows the principle of operation and the components of NectarCAM. The focal plane instrumentation, composed of light guides, PMTs and associated electronics, records light continuously. Light is converted into an analogue electrical signal which is sent in parallel to a data path and a trigger path. The trigger path continuously evaluates the trigger conditions. The signals are sent to analogue memories which act as circular buffers. When the trigger conditions are fulfilled, the data from a 10-60 ns region of interest in the analogue memories are digitized and processed in an FPGA located on the Nectar board, and sent by Ethernet to a camera server.

*http://cta-observatory.org

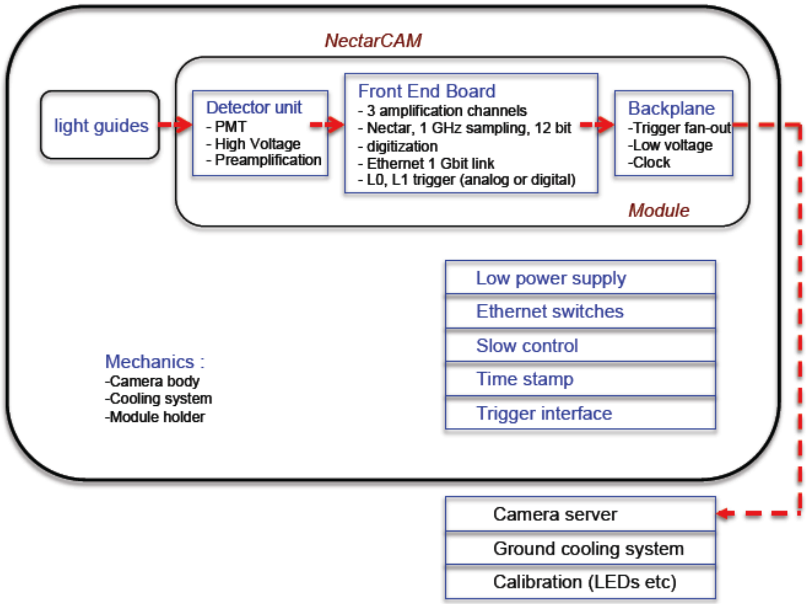

Figure 1. Principle of operation and components of NectarCAM

The camera has to be cooled to increase the lifetime of the electronics and reduce the calibration systematics. The camera just described is a complex system made of many parts which have to be designed, then tested and finally assembled. The next section describes the prototyping strategy of NectarCAM.

3. PROTOTYPING STRATEGY

The NectarCAM consortium includes fourteen institutions from France, Spain and Germany. Most of the components of NectarCAM are developped in common with teams designing other telescopes in the CTA consortium, particularly the Large Size Telescope (LST). The Nectar module is the only component which is developped specifically for NectarCAM. It is designed by a joint LPNHE/IRFU/ICC-UB/UCM-GAE/CIEMAT/IFAE/LLR effort. Other components include the trigger and timing instrumentation which is developped by CIEMAT/IFAE/UCM-GAE/DESY/APC, the focal plane instrumentation (IRAP/IPAG/ICC-UB), mechanics (LLR/CIEMAT/IRFU), slow control, services and monitoring (LAPP/IFAE), data acquisition (CPPM/IRFU/LUPM).

All these components are tested independently (see Sections 6, 5, 7) . A five-module prototype, which is used to test the trigger and data acquisition, is currently in operation. A larger 133-pixel, 19-module prototype is now being designed. It will be a true mini-camera and will include mechanics, cooling, slow control and services. The 19-module prototype will permit the validation of the concept and all the components of NectarCAM. The full data acquisition and control systems will be also tested. The next step will be the construction of a full size camera in 2015 and 2016.

4. TRIGGERING OF NECTARCAM

NectarCAM can be triggered externally for calibration purposes or internally for data acquisition. The triggering decision is sent to the camera modules by a trigger interface board. The data acquisition of NectarCAM is triggered in a multilevel scheme, shown in Figure 2. The first level trigger (L0) is a module-level trigger. The information from several modules is combined to realize a camera-level trigger (L1). The L1 trigger decision is made on a backplane board (see Section 6). The L0 and L1 trigger can be implemented with an "analogue"[3] or a "digital" solution. The trigger decision can also be purely local, implying just neighbouring modules, or global on the whole camera. The analogue trigger performs an analogue sum of the ouput of neighbouring pixels. In the digital solution, the 7 pixels are directly digitized and sent to the backplane. Flexible trigger solutions that

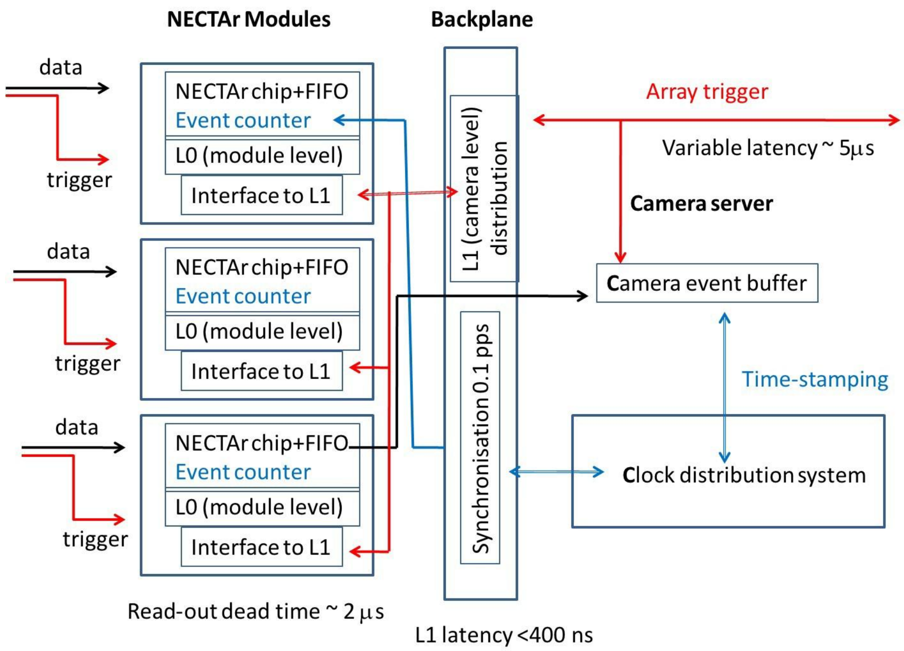

Figure 2. Triggering scheme of the NectarCAM camera.

minimize the dead-time and have the ability to read-out only partially the camera have been investigated.[4] The latency of the camera trigger is less than 400 nanoseconds. This is much less than the depth of the switched capacitor array in the NECTAr chip (1 μs at 1 GHz sampling rate), so that trigged events can be read from the analog memories. The trigged events are time-stamped on the trigger interface board before being sent to a camera server by ethernet. Since IACT arrays work in stereoscopic mode, events on the camera server are accepted only if they are coincident with triggers from one or several other telescopes. The typical trigger rate of a single telescope is 5 kHz. The latency of the array trigger is a few μs. Single telescope events have to be time stamped with a systematic error of less than (~ 2) nanoseconds. The analogue and digital trigger solution have been tested with several NectarCAM modules. The time resolution of the digital trigger was measured to be ~ 2 ns. A more extensive evalutation of both solutions is being performed on the 5-module prototype.

5. FOCAL PLANE INSTRUMENTATION

The focal plane of the NectarCAM camera is equipped with *detector units*, composed of a photo-detector, the associated high voltage power supply, and a preamplifier mounted on interface board. CTA has decided to use PMTs for the photodetectors of their single mirror telescopes. A candidate PMT is the R12992-100 developed by Hamamatsu†. The PMT is operated at the low gain of $4\ 10^4$ to allow camera operation during full moon. The R11920-100 PMT has a single photon electron signal FWHM of 2.5 to 3 ns. The light from the dead spaces between PMTs will be collected by custom designed Winston cones or lenses. The power supply of the PMTs is obtained from a custom designed Cockroft-Walton generator. Since the PMTs operate at low gain, their output has to be pre-amplified by a wideband (450 MHz) 16-bit amplifier called PACTA.[5] The high voltage and preamplification functionnalities of the HVPA are integrated on the HVPA board (right hand side of Figure 3) The focal plane instrumentation, light guides, PMTs and HVPA boards are tested on an optical bench at IRAP (Figure 3).

6. READOUT

As shown in Figure 4, signals from seven detector units are sent to a a front-end board and amplified again in an ACTA[6] ASIC.

† www.hamamatsu.com

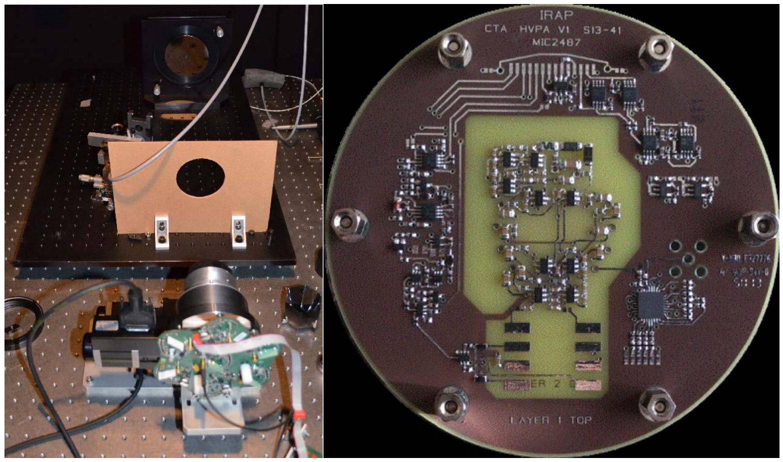

Figure 3. Test benches of components of NectarCAM. Left: Optical test bench for the focal plane instrumentation at IRAP. Right: High Voltage and Preamplification (HVPA) part of a detector unit.

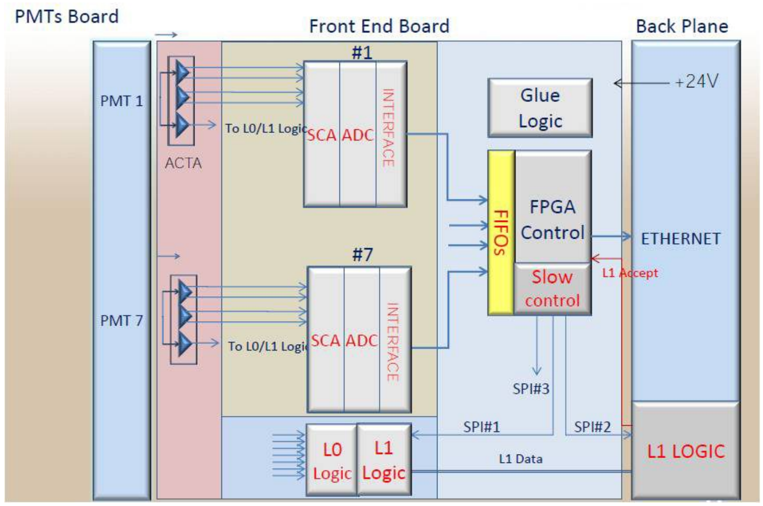

Figure 4. Principle of NECTAr readout modules.

At this level, the signal is divided into a low-gain, high-gain (relative gain 16) and a trigger channel. The two first levels of the trigger (L0 and L1) are temporarily implemented as mezzanines on the read-out board. The outputs of the low-gain and high-gain channels of the ACTA are sent to a NECTAr chip.[7] The NECTAr chip has the dual functionality of switched capacitor array and analog-to-digital convertor. The switched capacitor array, which acts as a circular buffer, has a depth of 1024 samples and can be operated between 500 MHz and 3.2 GHz. The NECTAr chip has a bandwidth of more than 400 MHz and a dynamic range of 11.3 bits. The power consumption is 210 mW. The NECTAr chip is thus a low power, cheap alternative to the use of a Flash-ADC (FADC). The dead time is 2 μs for the readout of 16 capacitor cells and increases linearly with the number of cells. Since the maximal expected trigger rate from NectarCAM is expected to be 9 kHZ, the readout of 16 cells from NECTAr chips contributes 2% dead time for the camera. The dead-time would increase to 10% for the read-out of 60 ns time-windows. However, using a flexible trigger such as the one described by Naumann et al[8] allows a long signal to be recorded without increasing the dead-time. Once an L1 trigger signal is emitted, the data from a 16-20 ns time interval around the time of the trigger are read out. They are retrieved from the NECTAr chip and sent to a FPGA located on the front end board. This FPGA has several functions: interface to the Ethernet, control of the NECTAr chip, of the L0, L1 trigger configurations, and the HV power supply. High level quantites such as the integrated charge over the readout window and the arrival time of the signal can be calculated inside the FPGA. The system can be configured to send these quantities over the Ethernet connection instead of the full event waveform.

The backplane board located on the right hand side of Figure 4 is used for clock and synchronisation signal distribution, low voltage (24 V) power distribution, L0 trigger fan-out and L1 trigger distribution. In some trigger schemes, one of the backplane boards could be used to make the L1 (camera) trigger decision. The readout board has been tested with PMT and electrical pulser signals (left hand side of Figure 5). Charges between 0.2 and 2000 photo-electrons can be measured with the two gain channels. The charge response is linear to better than 5% over the whole usable energy range. The single photoelectron peak (right hand side of Figure 5) can be measured for calibration purposes

7. MECHANICS AND COOLING

All the scientific equipment and internal mechanical components are enclosed in an aluminium structure shown on Figure 6. The camera will be exclude to avoid dust and moisture. One possibility for sealing the camera aperture is to use a plexiglass window. The camera will have $\sim$ 1800 PMTs grouped in $\sim$ 265 modules. These modules are inserted into a tubular structure called the "camera body" . The rest of the internal equipment (services, communication and electrical interface with the exterior, cables) are held by mechanical fixtures such as small racks, wiring ducts and electrical cabinets. The weight of the camera is less than 2 tons. The total power consumption is of the order of 7.4 kW. When not taking observations, the front of the camera will be sealed by a rolling shutter. The front of the camera may also hold equipment for the electronics calibration (e.g. a Mylar plate for the single photo-electron calibration) and for the pointing calibration (positioning LEDs, reflecting screen).

Since the camera is sealed, proper care must be taken to avoid overheating of the electronics. NectarCAM will use a system with a mixture of a water-cooled plate and forced airflow. The requirement for that system was to obtain a temperature gradient of less than 10 ° C across the clusters. It was first simulated (left hand side of Figure 8). The simulation was then checked with a thermal demonstrator which is shown on figure 7. The thermal demonstrator has a simplified version of half the mechanics of the camera body, with simulated front end boards delivering up to 3 kW power. The right hand side of figure 8 shows a cooling sequence at several points of the thermal demonstrator. The preliminary study shows that the temperature difference is everywhere less that 10 ° C and thus validates the cooling system. The cooling plates were not included yet in the demonstrator. They could be useful to control the temperature gradient in the focal plane.

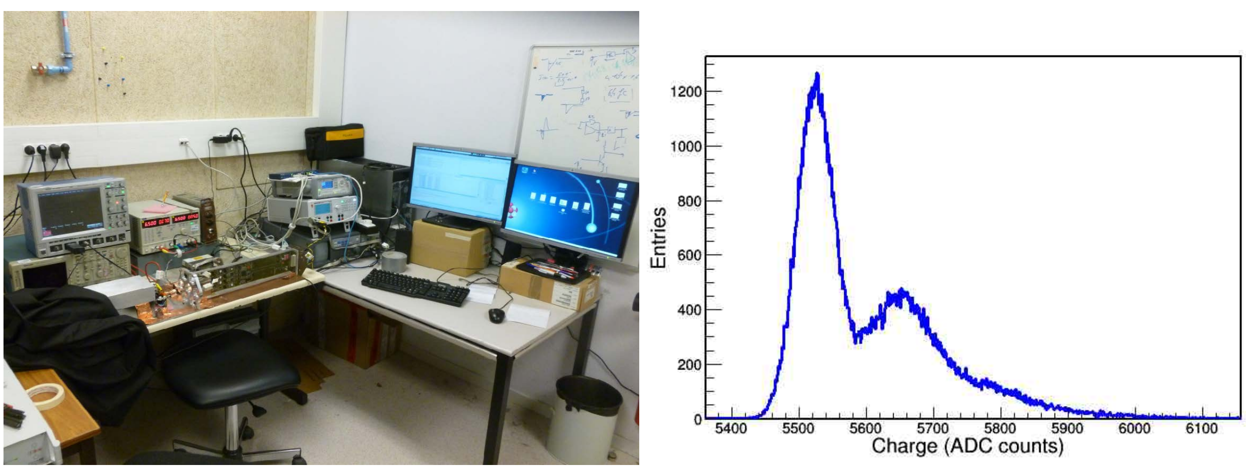

Figure 5. Left: Single module test bench at LPNHE. Right: Single photoelectron spectrum obtained with the NectarCAM V1 module. Light from a LED is captured with a PMT operating at a gain of $4 \cdot 10^4$, then amplified by a PACTA and an ACTA amplifier and finally sampled and digitized in the Nectar chip.

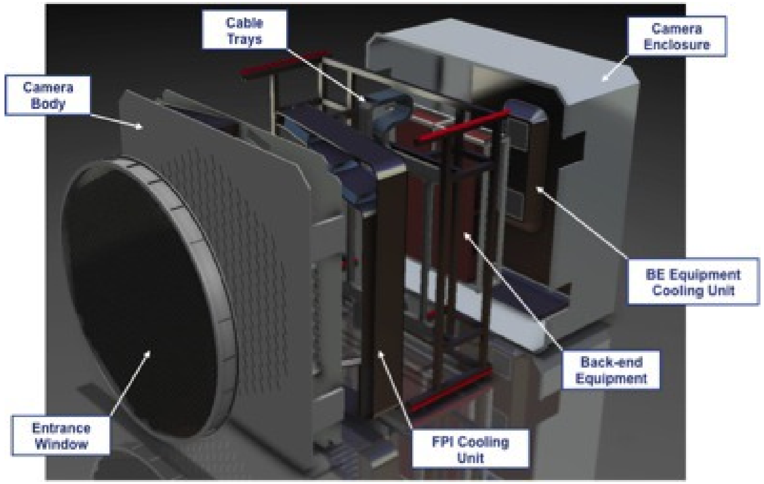

Figure 6. Exploded view of the NectarCAM camera mechanics.

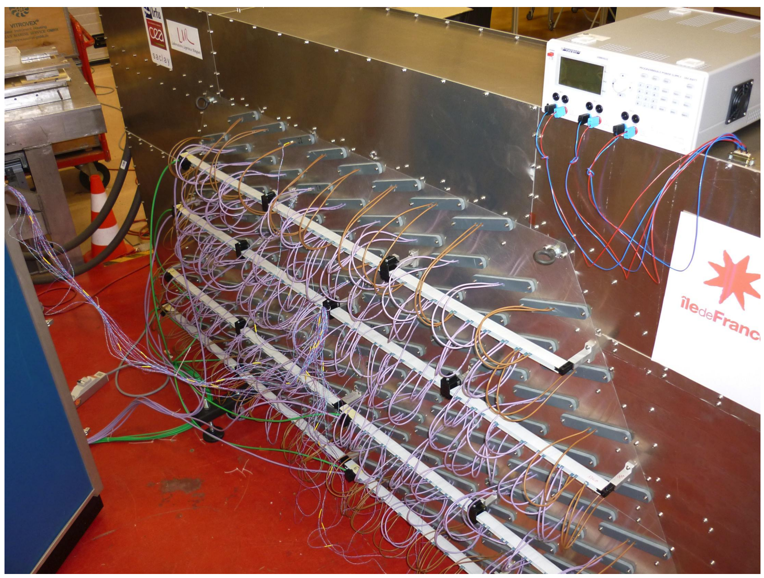

Figure 7. Thermal demonstrator for the design of NectarCAM mechanics

8. SLOW CONTROL AND SERVICES

NectarCAM will have sensors to monitor the temperature, pressure and humidity inside the camera. Its safety will be ensured with ambient light sensors, smoke detectors and by tracking the position of the shutters and back doors. Most subsystems of the camera are controlled remotely. This is the case for the calibration-related hardware (positioning leds), the cooling system, the trigger interface board and the clock distribution board. The slow control will be managed by a controller located inside the camera. This controller could be a Compact RIO crate [‡], or a custom made board with e.g. a SoC from Altera [§]. The sensors are accessed by industrial buses such as I2C. Custom-made sensor modules for temperature, pressure, humidity, acceleration measurements have been designed (l.h.s of figure 9) and are under test. The use of the OPCUA[¶] industrial standard will allow the control system to be easily incorporated in the full CTA array control. The slow control server and the sensors will be installed on the 19-module camera demonstrator in 2014.

[‡]http://www.ni.com/compactrio

[§]http://www.altera.com/devices/processor/soc-fpga/overview/proc-soc-fpga.html

[¶]https://opcfoundation.org/about/opc-technologies/opc-ua/

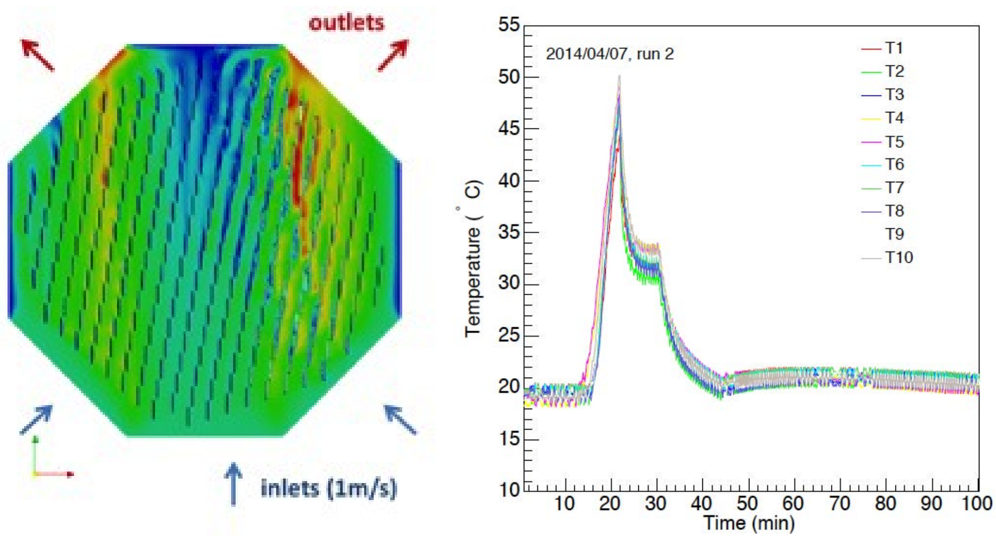

Figure 8. Left: Simulation of a cooling airflow in the NectarCAM sandwich. The sandwich hosts ∼ 265 NECTAr modules.Right: Preliminary results from the thermal demonstrator.

The external services will be power and cooling. The components of NectarCAM are powered with 24 V.

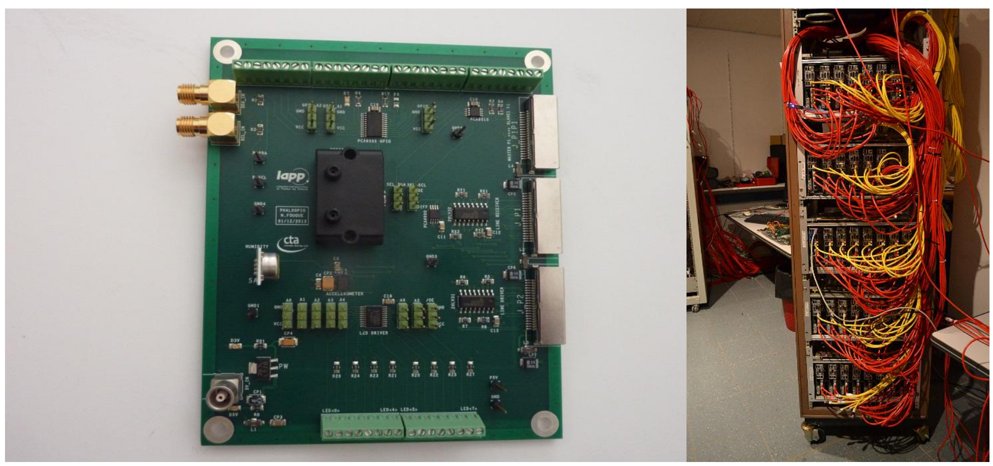

Figure 9. Left: custom-made pressure, humidity and acceleration I2C sensor. Right: stimulator of the NectarCAM data acquisition system (see text for explanations)

9. DATA ACQUISITION

The data acquisition follows the model described by Hoffmann and Houles.[9] Data from NECTAr modules are sent to the camera server by a UDP connection, through seven commercial Ethernet switches. The switches are linked to the camera server through three 10 Gbit connections. The data rate between a NECTAr module and the switches is 2 Mbit/s, if only the total charge and arrival time of pixels are transferred. It is ∼ 40 Mbit/s if the full waveform is transferred. Since the arrival time of the camera event is random, it may happen that a burst of events overflows the switch buffers. This aspect of data acquisition is being studied with a "stimulator". The right hand side of Figure 9 shows five DAQ stimulator crates to simulate up to 200 Nectar front-end module outputs at 20kHz average event rate and 1Gbps Ethernet speed. The stimulator will be installed on the 19-module camera demonstrator to simulate the full acquisition of NectarCAM.

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